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Measurement of the Higgs boson mass from the $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ channels with the ATLAS detector at the LHC.

Andrea Gabrielli

Sapienza Università di Roma and INFN Sezione di Roma 1, Piazzale Aldo Moro 2, 00185, Roma, Italy.

E-mail: andrea.gabrielli@cern.ch

Abstract

This document presents an updated measurement of the Higgs boson mass with the combined fit of two decay channels $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$. The analyses are based on 4.5 fb^{-1} and 20.3 fb^{-1} of proton-proton collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV respectively, recorded with the ATLAS detector at the LHC. This result includes improved energy-scale calibrations for photons, electrons, and muons, as well as other analysis improvements.

1. Introduction

The measurement of the Higgs boson mass based on improved analyses of the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ channels is presented. The $H \to \gamma\gamma$ channel profits from an improved calibration of the energy measurements of electron and photon candidates, which results in a sizable reduction of the systematic uncertainties on their energy scales. In the $H \to ZZ^* \to 4\ell$ channel both the expected statistical uncertainty and the systematic uncertainty on the mass measurement have been reduced with respect to the previous publication. The improvement of the statistical uncertainty arises primarily from the use of a multivariate discriminant that is designed to increase the separation of the signal from background. The systematic uncertainty reduction comes from both the improved electromagnetic energy calibration and a reduction in the muon momentum scale uncertainty [1].

2. $H \to \gamma\gamma$

The $H \to \gamma\gamma$ channel provides good sensitivity to the Higgs boson mass, due to the high mass resolution in the di-photon final state. The signature of this channel is a narrow mass peak over a smooth background which can be determined directly from data. The EM calorimeter provides a measurement of the photon energy and direction, utilizing its longitudinal segmentation. The typical mass resolution is 1.7 GeV for a 125 GeV Higgs boson mass. The main background is continuum $pp \to \gamma\gamma + X$ production with smaller contributions, of about 20%, from the $\gamma + jet$ and di-jet processes.

2.1. Event selection and categorization

Events are selected using a di-photon trigger. For the 7 TeV data, a threshold of $E_T = 20$ GeV is required to both photons at the trigger level. For 8 TeV data, the E_T threshold at the trigger level is 35 GeV for the photon with the highest E_T and 25 GeV for the second one. Only photon candidates with $|\eta| < 2.37$ are considered, except the transition region $1.37 < |\eta| < 1.56$ between the barrel and end-cap calorimeters. The calorimeter and track isolation are applied. The final di-photon invariant mass $m_{\gamma\gamma}$ is computed using the measured photon energies and their opening angle estimated from the selected primary vertex and the photon impact points in the calorimeter, exploiting its longitudinal segmentation. Additional cuts are applied to the two photons: the transverse energy is required to be $E_T > 0.35 \times m_{\gamma\gamma}$ for

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the photon with the highest E_T and $E_T > 0.25 \times m_{\gamma\gamma}$ for the second one. This selection leads to a smoother background distribution in each of the event categories compared to using fixed cuts on E_T. To improve the accuracy of the mass measurement, the selected events are separated into ten mutually exclusive categories. The categorization, is optimized to minimize the expected uncertainty on the mass measurement. Events are separated into two groups, one where both photons are unconverted and the other where at least one photon is converted. Then the events are classified according to the η of the two photons: the central category corresponds to events where both photons are within $|\eta < 0.75$ (highest resolution), the transition category corresponds to events with at least one photon with $1.3 < |\eta| < 1.75$, and the rest category corresponds to all other di-photon events. Finally, the central and rest categories are each split into a low $p_{Tt}(< 70\,\text{GeV})$ and a high $p_{Tt}(> 70\,\text{GeV})$ category, where p_{Tt} is the component of the di-photon transverse momentum orthogonal to the diphoton thrust axis in the transverse plane.

2.2. Results

Figure 1 shows the result of the simultaneous fit to the data over all categories, where all categories are summed together, with a weight given by the signal to background ratio in each category. The dominant systematic uncertainties on the mass measurement arise from uncertainties on the photon energy scale. The measured Higgs boson mass in the $H \to \gamma\gamma$ decay channel is:

$$125.98 \pm 0.42\,(\text{stat}) \pm 0.28\,(\text{sys})\,\text{GeV}$$

The mass measurement is performed leaving the overall signal strength free in the fit as a nuisance parameter. The measured signal strength, μ, normalized to the Standard Model expectation is found to be $\mu = 1.29 \pm 0.30$.

3. $H \to ZZ^* \to 4\ell$

The $H \to ZZ^* \to 4\ell$ channel provides good sensitivity to the measurement of the Higgs properties due to its high signal-to-background ratio, and its high mass resolution, for each of the four final states. Furthermore, it offers a clear, clean signature, a narrow peak in the fourlepton invariant mass over a flat background. The typical mass resolution varies from 1.6 (2.2) GeV for the $4\mu(4e)$ final state. The dominant background is the ZZ^* process and a smaller contribution is expected from the Z + *jet* and $t\bar{t}$ processes.

3.1. Event selection

Four-lepton events are selected with single-lepton and di-lepton triggers. The p_T (E_T) thresholds for single-muon (single-electron) triggers increased from 18 GeV to 24 GeV (20 GeV to 24 GeV) between the 7 and 8 TeV data sets, due to the increase of the instantaneous luminosity during these two data-taking periods. The di-lepton triggers have thresholds starting at 6 GeV (10 GeV) for muons (electrons) for 7 TeV data. For the 8 TeV data, the di-lepton trigger thresholds were raised to 13 GeV for the di-muon and to 12 GeV for the di-electron. Each lepton is required to have a longitudinal impact parameter less than 10 mm with respect to the primary vertex. Each muon (electron) must satisfy $p_T > 6\,\text{GeV}$ ($E_T > 7\,\text{GeV}$) and be measured in the pseudorapidity range $|\eta| < 2.7$ ($|\eta| < 2.47$). The highest p_T lepton in the quadruplet must satisfy $p_T > 20\,\text{GeV}$, and the second (third) lepton in p_T order must satisfy $p_T > 15\,\text{GeV}$ ($p_T > 10\,\text{GeV}$). For each channel, the lepton pair with the mass closest to the Z boson mass is selected as the leading di-lepton pair and its invariant mass m_{12} is required to be between 50 GeV and 106 GeV. The second, subleading, pair of each channel is chosen as the pair with its invariant mass m_{34} closest to the Z mass, and also satisfying $12 < m_{34} < 115\,\text{GeV}$. The Z + *jet* and $t\bar{t}$ background contributions are further reduced by applying impact parameter and track- and calorimeter-based isolation requirements to the leptons. The impact parameter significance, $|d_0|/\sigma_{d_0}$, for all muons (electrons) is required to be less than 3.5 (6.5). The normalized track isolation discriminant, defined as the sum of the transverse momenta of tracks inside a cone of size $\Delta R = 0.2$ around the lepton, is required to be smaller than 0.15. The normalized calorimetric isolation is required to be smaller than 0.2 (0.3) for electrons in the 7 TeV (8 TeV) data, and smaller than 0.3 for muons (0.15for standalone muons).

3.2. Multivariate discriminant

The multivariate discriminant used to reduce the impact of the ZZ^* background on the fitted mass is based on a boosted decision tree (BDT). The BDT classifier is trained using simulated signal events generated with $m_H = 125\,\text{GeV}$ and simulated ZZ^* background events that pass the event selection and have $115 < m_{4\ell} < 130\,\text{GeV}$. The variables used in the training are the transverse momentum and the pseudorapidity of the four-lepton system, plus a matrix-element-based kinematic discriminant (D_{ZZ^*}) defined as:

$$D_{ZZ^*} = \ln \frac{|ME_{sig}|^2}{|ME_{ZZ^*}|^2}$$

where ME_{sig} and ME_{ZZ^*} are the matrix elements for the signal and ZZ^* background processes, respectively, computed at leading order using MadGraph.

3.3. Results

Figure 2 shows the $m_{4\ell}$ distribution of the selected candidates for 7 and 8 TeV data. The main sources of systematic uncertainties on the mass measurement are the electron energy scale and the muon momentum scale. The expected impact of these uncertainties on the mass measurement corresponds to about 60 MeV for both the $4e$ and the 4μ channels, obtained from the 2D fit to simulation. The measured Higgs boson mass in the $H \to ZZ^* \to 4\ell$ decay channel obtained with the baseline 2D method is

$$124.51 \pm 0.52\,(\text{stat}) \pm 0.06\,(\text{sys})\,\text{GeV}$$

the measured signal strength for this inclusive selection is $\mu = 1.66^{+0.45}_{-.38}$.

4. Combined measurement

4.1. Statistical procedure

The invariant mass spectra of the two channels $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ are fit to a common mass m_H combining the individual inputs. In this measurement the signal strengths can vary independently, where both signal strengths $\mu_{\gamma\gamma}(m_H)$ and $\mu_{4\ell}(m_H)$ are treated as nuisance parameters (NPs), to make no assumptions about its couplings.
For the combined mass measurement of Higgs boson, hypothesized values of m_H are tested using the profile likelihood ratio defined in terms of m_H:

$$\Lambda(m_H) = \frac{L(m_H\,,\,\hat{\hat{\mu}}_{\gamma\gamma}(m_H)\,,\,\hat{\hat{\mu}}_{4\ell}(m_H)\,,\,\hat{\hat{\vec{\theta}}}(m_H))}{L(\hat{m}_H, \hat{\mu}_{\gamma\gamma}, \hat{\mu}_{4\ell}, \hat{\vec{\theta}})}\,. \qquad (1)$$

where, $\vec{\theta}$ is the ensemble of nuisance parameters, the single circumflex denotes the unconditional maximum likelihood estimate of a parameter and the double circumflex (*e.g.* $\hat{\hat{\vec{\theta}}}(m_H)$) denotes the conditional maximum likelihood estimate (*e.g.* of $\vec{\theta}$) for given fixed values of m_H. The leading source of systematic uncertainty in the mass measurement comes from the energy-momentum scale uncertainties of the main physics objects used in the two analyses, muons and electrons for the $H \to ZZ^* \to 4\ell$ and photons for the $H \to \gamma\gamma$ final state, respectively.

4.2. Results

From the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$ combination the common mass is estimated to be

$$m_H = 125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{sys})\,\text{GeV}$$

where the first error represents the statistical uncertainty and the second the systematic uncertainty. The compatibility between the mass measurements from the two individual channels is at the level of 2.0σ corresponding to a probability of 4.8%.

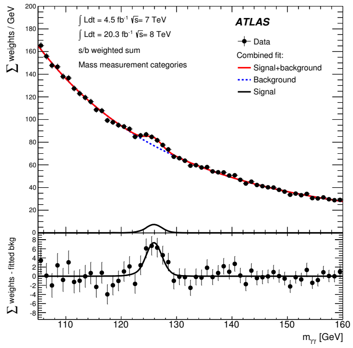

Figure 1: Invariant mass distribution in the $H \to \gamma\gamma$ analysis for data, showing weighted data points with errors, and the result of the simultaneous fit to all categories.

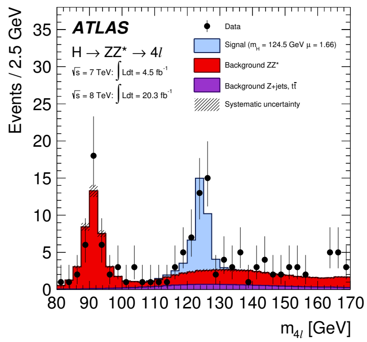

Figure 2: Distribution of the four-lepton invariant mass for the selected candidates in the $m_{4\ell}$ range $80 - 170$ GeV, superimposed are the expected distributions of a SM Higgs boson signal for m_H = 124.5 GeV normalized to the measured signal strength, as well as the expected ZZ^* and reducible backgrounds.

References

[1] ATLAS Collaboration, *Measurement of the Higgs boson mass from the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ channels with the ATLAS detector using 25 fb^{-1} of pp collision data* , PR D 90, 052004 (2014), `arXiv:1406.3827v1 [hep-ex]`.